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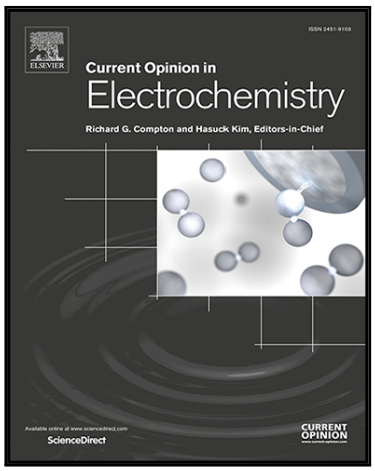

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Highlights

- wide range of in-situ electrochemistry of Au-S bound molecular targets overviewed
- physisorbed and chemisorbed sulfur ligands to gold show great diversity
- Au(I)-thiolates destroy surfaces and nanoparticles
- Au(0)-thiyl species stabilize surfaces
- chemisorptive and physisorptive bindings share common key properties

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Sulfur ligand mediated electrochemistry of gold surfaces and nanoparticles: what, how, and why

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Abstract

Gold surfaces are widely used in electrochemistry whilst gold nanoparticles have very many uses, with both the surfaces and the particles often being protected by sulfur-bound organic ligands. The ligands not only provide chemical stability but also directly participate in many desired processes. This review considers the diversity of known atomic structures for gold-sulfur interfaces, how these structures facilitate a diversity of mechanisms in electrochemical applications, and why this is possible based on recent advances in the basic understanding of the electronic structure of gold-sulfur bonds. Believed once to be Au(I)-thiolate in character and hence distinctly different to physisorbed thiols and disulfides, chemisorbed bonds are shown to be Au(0)-thiyls instead. A wide range of in-situ STM electrochemical and other data is interpreted from this perspective.

Keywords

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Au-S surface bonding; atomically planar Au-surfaces; Au-nanoparticles; Thiol chemisorption on Au-surfaces; Adsorption of large molecules and biomolecules; Electrochemistry; In-situ electrochemical STM

1. Introduction

For thousands of years, solid gold (Au) has been treasured as an economic investment, for cultural purposes, and as jewelry [1]. Since antiquity, Au-nanoparticles (AuNPs) have also been manufactured for their unique physical properties adorning glass and other surfaces as decorations [1–3]. In modern times, Au surfaces and AuNPs are widely used in, e.g., heterogeneous catalysis, electrochemistry and electrocatalysis [4–7], molecular electronics [8,9], fuel and biofuel cells [10,11], and in medical diagnostics and therapy [12–14].

To prevent clogging and the effects of harmful reagents, AuNPs have to be protected by self-assembled monolayers (SAMs), a bit like tea in a teapot brought to preserve taste and warmth by a tea cosy [15–17]. Similarly, Au-surfaces can be protected or functionalized by SAMs, with organic thiol compounds, RSH having acquired a unique status [1,18–22] as these electronically "soft" ligands bind well to electronically "soft" surface Au-atoms [23]. The functionalizing residues R can be hydrophobic or hydrophilic, electrostatically charged or neutral, or spatially large or small [1,18]. The multifarious RSH residues can therefore impose almost tailor-made Au-surface properties, reflected in a broad variety of molecular and biomolecular adsorption and electrochemical electron transfer (ET) patterns, in which the surface Au-S bond is the central electronic contact.

This review considers the basic elements of the gold-sulfur links that make up these critical interfaces: what are they, how can they be put to work, and why they facilitate so many ancient and modern applications.

2. What is the structure of sulfur-bonded ligand-protected gold surfaces and nanoparticles?

The atomic structure is a common element of gold-sulfur interfaces with properties independent of intended function, be this electrochemical in nature or otherwise. Indeed, a wide variety of alkanethiol-bound monolayers or just isolated single molecules have been used [24,25], including molecules with sophisticated electrochemical function [26–29] intended, e.g., for in

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molecular scale electronics [9]. To answer the question "What?", we focus on simple systems without explicit function that disclose critical structural questions.

Many simple systems, like those highlighted in Figs. 1 and 2, in both aqueous electrolytes and ionic liquids have been studied [18,30–33]. A highly beneficial combination of electrochemistry at single-crystal Au-electrode surfaces, electrochemically controlled scanning tunneling microscopy (in-situ STM), X-ray photoelectron microscopy (XPS), and break-junction technology has been used [18,26–28,31,32,34,35]. Not only static imaging, but also dynamics of molecular surface conformational changes, and even the whole SAM formation process have been mapped to single-molecule resolution [31,36]. State-of-the-art theoretical and computational work has been paramount in the interpretation of the multitude of physical and chemical data, being useful in determining the factors that control structure such as Au-S bonding, intermolecular surface interactions, and solvation [25,32,33,35–40]. This work complements that done by others under ultrahigh vacuum conditions, emphasizing both adsorbate STM imaging [24,41–43] and surface spectroscopy [44], as well as X-ray crystallographic studies [45].

Fig.1

Fig.2

Particularly illuminating for understanding the diversity of available interface atomic structures is the class of the four straight and branched butanethiols [25,35]. The butanethiols (Fig. 2) are: 1-butanethiol [33], 2-methyl-1-propanethiol [32], and 2-methyl-2-propanethiol (tert-butanethiol) [39,46], molecules that are all achiral, as well as the chiral pair (R)- and (S)-1-methyl-butanethiol [25,37]. The data illustrate the amazing detail extracted from this approach:

- In spite of their similar structures, the butanethiols display widely different adsorption modes, disentangled in minute structural detail. Mapping of other functionalized alkanethiols have been resolved in comparable detail [18].

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- The butanethiol packing at high coverage is determined primarily by Au-S bonding and lateral intermolecular interactions. Solvation is a determinant for functionally charged alkanethiols such as cysteamine [18,36] and cysteine [18,30].

- The Au-S bond for even the butanethiols of modest structural sophistication leads to multifarious Au-surface packing. Binding of straight chain 1-butanethiol is via molecular extraction of an Au-atom ("atomic gold mining") from the Au(111)-surface, leaving a surface vacancy, followed by sideway binding of two adsorbate molecules [24,32,33,35,40]. Surface vacancies typically coalesce into surface pits. There is no space for this binding mode for the bulky *tert*-butanethiol 2-methyl-2-propanethiol which is the only butanethiol that binds solely on a flat Au (111)-surface.

- Binding of the chiral pair of (R) and (S)-2-butanethiol is particularly intriguing [25,37]. The individual (R) and (S) enantiomers bind via "atomic mining", i.e. by Au-atom extraction from the Au (111)-surface. The racemic mixture binds in both a low-density (coverage 25 %) and a high-density (coverage 30 %) phase. While the low-density phase is bound by atomic gold mining, to squeeze in more butanethiol molecules in the high-density phase, both atomic gold mining and direct Au-S adsorption operate, Fig. 2. This is highly unusual, with both binding modes operating on the same surface.

3. How can sulfur-bonded ligand-protected gold surfaces and nanoparticles be put to work?

The importance of molecules bound to Au-electrodes via pendant S-linker groups is strongly illustrated in electrochemical STM and break-junction experiments. Examples of more sophisticated Au-S based redox molecules characterized at single-molecule resolution by in-situ STM technology and voltammetry on single-crystal electrodes are shown in Fig. 3 [26,27,29,47–49]. The viologens and tetrathiafulvalenes shown [26–28], as well as the shown transition metal complexes of ruthenium, osmium and cobalt [29], provide paradigms describing this field. These molecules display in-situ scanning tunneling current/overpotential spectroscopy (STS) consistently rationalized as two-step sequential electron transfer (ET) between tip and working electrode via the molecule. Theoretical frameworks for understanding of Au-S molecular redox systems such as these have so far rested on phenomenological, although comprehensive views and models [48]. These have met with success for organic redox molecules [26,27], transition

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metal complexes [29], redox metalloproteins [34,50,51], and Au-S bound DNA based molecules [52].

Fig.3

As particular examples, monolayer voltammetry of redox metalloproteins and DNA-based molecules has evolved [34,48,50–57]. Much current effort is on applied aspects such as biosensing [6,12,13], electrocatalysis [2,3,5,6,58,59], biofuel cells [10,11], and bioelectrochemistry on living systems [60]. The fundamental electrochemical ET processes are, however, also in focus, and structural and electrochemical mapping of single redox metalloprotein and DNA-based molecules, using techniques and new theory of in-situ STM/STS, has emerged over the last decade [27,34,48,50,53,54].

A key aspect of "how" concerns how retaining ET and other natural function of fragile biological macromolecules on electrochemical surfaces almost always rests critically on electrode preparation. Surface preparation immobilizes the macromolecules gently enough that conformational protein structural changes are insignificant. Chemisorbed Au-S bond formation is a core link in protein immobilization, but mostly via SAMs of functionalized alkanethiols, the remote, hydrophobic or charged tail group of which provides a non-covalent link to the protein [48,61,62]. The reactivity of the immobilized redox metalloproteins is, however, exceedingly sensitive to the structural details of the SAM. This is strikingly illustrated by the voltammetry and in-situ STM and AFM studies of the blue Cu-enzyme nitrite reductase on single-crystal Au(111) electrode surfaces, modified by a broad variety of aliphatic and aromatic thiol SAMs [63,64].

An example of a robust single-molecule-based bioelectrochemical electronic behavior based on chemisorbed Au-S head-group interactions is the four-α-helix bundle bacterial protein cyt b_{562} (*Escherichia coli*) shown in Fig. 4 [50]. Mutations in this protein could introduce cysteine (Cys) residues at chosen locations on the outside of the protein. The success of the approach is indicated by the observation of almost ideal protein film voltammetry on single-crystal Au (111)-electrode surfaces; also in situ STS displayed the expected tunneling-current/overpotential STS. The results are intriguing, however, in that single or multiple attachments at different positions on the ellipsoidal protein is naively expected to give quite different redox behavior and different ET pathways through the protein yet little variation was

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actually observed [50]. In addition, the observed cyt b_{562} conductivity was almost ten times higher than nearly all reported in-situ redox single-molecule conductivities. Coherent multi-ET has been suggested as a rationale [50], but the question as to the nature of the possibly strained Au-S bonds involved is also raised.

Fig.4

Further insight into this can be gained by considering the blue-Cu azurin protein from Pseudomonas aeruginosa. Early work [48,54] was continued by other groups [34,51] targeting mutant azurins with introduced surface Cys residues linking the protein to an enclosing Au-surface and Au-tip [34]. A feature of this system first theoretically predicted [48] is that in situ STS displays a tunneling current maximum [34,51,66]. This feature has now been observed for three azurin binding modes, hydrophobic binding to alkanethiol SAMs [66], physisorbed disulfide binding to an Au tip [51], and chemisorbed Au-S binding via inserted mutant Cys residues [34].

However, physisorptive binding of metalloproteins via –SH or -S-S- groups rather than chemisorbed Au-S bonds involving wild type proteins with retained voltammetric activity is actually rare. The nature of the bonding is therefore just as important as the atomic configuration in understanding "how" electrochemical devices function. Still another notable case is yeast cytochrome *c* [67,68]. The linking chemisorbed –SH group in this case is, however, located slightly below the protein surface, and both conformational reorganization and a low-spin/high-spin transition in the axial heme ligand structure in the protein accompanies binding to the surface. Also, we note that human insulin adsorbs on all three low-index Au-surfaces, Au(111), Au(100) and Au(110) via intrinsic disulfide groups, mapped to single-molecule resolution by in situ STM [65]. How sulfur-bounded ligand-protected surfaces can be put to work is therefore quite complex.

4. Why does the nature of the Au-S bond make sulfur-bonded ligand-protected gold surfaces and nanoparticles so versatile?

The questions of "what" and "how" thus both lead to significant questions concerning how it is that sulfur-bonded ligand-protected gold surfaces are so versatile. The Au-S bond can take on vastly different chemisorbed geometries and coordinations, and can still function even through much weaker physisorbed connections. There must be a unifying bonding feature that allows for

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this diversity, explaining "why" Au-S bonded molecular adsorption and molecular function works so well and can lead to practical devices.

Comprehensive spectroscopy, diffraction and other surface physics supported by theoretical and computational work has disclosed the nature of the Au-S bond [24,38,39,41–44,46,69,70]. These results are consistent with the in-situ STM & AFM studies [71] and provides a detailed understanding of structure and function [40]. For more than 30 years consensus has been that thiol adsorption involves a redox process

$$RSH + Au(0) \rightarrow RS^{-}\text{-}Au(I) + \tfrac{1}{2}H_2$$

The reverse process is electrochemical reductive desorption,

$$RS^{-}\text{-}Au(I) + e^{-} \rightarrow Au(0) + RS^{-},$$

with the electrochemical signals reflecting highly sensitively the general state of the SAM. Au(I)-thiolate bonds are well known in molecular Au-S complexes [72,73], forming a prime example of coordination between electronically "soft" metal ions and "soft" ligands [23]. The properties of Au atoms in planar Au surfaces are, however, quite different from those in simple compounds. A new analysis, supported prodigiously by computations and data shows instead that surface Au-S binding holds a dominant element of Au(0) and thiyl radical RS• character [40], character not too different from that found in physisorptive interactions of surfaces to thiols and disulfides. Direct contact of the thiolate anion with Au surfaces leads instead to etching or even dissolution [74]. This is a real physical distinction as the chemical and spectroscopic properties of Au(I)-thiolate and Au(0)-thiyl species are quite different.

A recent study [75] of Fe-porphyrin complexes with a Fe-Cys axial ligand that mimic the heme protein cytP450 offers a striking illumination. The Fe-Cys bond involves the equilibrium Fe(III)- $^{-}$SR $\leftrightarrows$ Fe(II)- •SR that resembles the resonance scenario Au(I)- $^{-}$SR $\leftrightarrow$ Au(0)- •SR. However, this equilibrium depicts real and tunable valence tautomerism between two different states distinguishable by significantly different spectroscopic properties, while Au(I)-thiolate/Au(0)-thiyl is instead viewed as presenting single resonance scenarios with different electronic charge distributions in the electronic ground and excited states.

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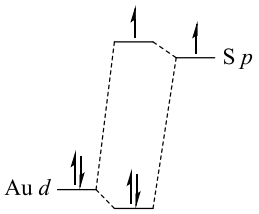
The electronic structure of Au is $5d^{10}6s^{1}$. Common belief has been that the Au-S bond to Au surfaces bond is covalent and dominated by the open shell 6s and 3p orbitals of Au and sulfur, with the Au 5d orbitals in a less prominent role [76]. However, strong Au-Au interactions within surface and in Au-Au compounds [72,73,77,78] shifts the 6s band away from the Au Fermi level and the 5d band [69], causing the filled 5d orbitals to take over bonding to the sulfur atom.



The bonding in such circumstances is often dominated by van der Waals dispersion forces as the interaction of a low-lying doubly occupied orbital with a high-lying one does not lead to significant covalent or ionic bonding [40]. In gold chemistry this is known as the "aurophilic effect" [72,79].

Binding schemes such as these are, however, limiting cases, mixed by s-d hybridization, polarization effects, multifarious coordination, etc. All computations and sophisticated experiments show, that Au(0)-thiyl is a tunable, highly significant structural component that typically dominates the binding of SR groups to surfaces. Related dispersion forces are also important for the binding of other electronically "soft" ligands like nitrogen bases and disulfides to Au surfaces, including as well situations where Au atoms are mined out of the surfaces [47]. This understanding rationalizes the wide range of geometrical structures at interfaces observed, as well as the robustness of their electrochemical properties.

5. Conclusions and perspectives

The Au-S bond on planar and AuNP Au surfaces is an important element that ties together binding and packing of a wealth of complex and less complex S-linked molecules and biomolecules on both electrochemical and non-electrochemical surfaces. Understanding the properties of this structural element is therefore paramount. On the basis of recent detailed analysis [40], it is concluded that the Au-S link holds a dominant Au(0)-thiyl character resting on strong van der Waals interactions and the aurophilic effect, in addition to secondary covalent and

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ionic Au-S features. There is thus a similarity and continuity between chemisorption and physisorption of sulfur compounds to gold. Aspects [40] of the Brust-Schiffrin core nanoparticle synthesis [16,17] can then be understood, as well the results of real time imaging on planar Au-electrode surfaces as reported for 1-propanethiol [31] and cysteamine [36], anticipated also for more complex molecular SAMs [80].

The nature of the Au-S link as a radical may indicate reactivity in addition to electrochemical reductive desorption. Mostly, however, radical character of the sulfurs is typically lost owing to long-range superexchange coupling that couples sulfur atoms together and diffuses the radical character into the gold metal [40,69]. Nevertheless, a study of the effect of O_2 on in-situ STM imaging of Au-S bound target molecules suggests that residual radical character can still be manifested [81]. This understanding may hold clues to the unexpectedly efficient long-range conductivity of most of the S-molecular classes discussed, not in the least the metalloproteins azurin and cyt b_{562}. Such long-range Au-S based surface electronic effects could be rationalized, if reactive intermediates in sequential or superexchange long-range ET via low-lying radical-derived intermediate states are involved. The new abundantly supported understanding of the Au-S surface bond is, finally likely to be of use in forthcoming efforts towards molecular scale switching, rectification, amplification, and other molecular electronics, as well as in approaches to Au-S based chemical and biological sensing, fuel cell electrocatalysis, and other developing electrochemical high-technology.

References and recommended reading:

Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- •• of outstanding interest

[1] M.-C. Daniel, D. Astruc, Gold Nanoparticles: Assembly, Supramolecular Chemistry, Quantum-Size-Related Properties, and Applications toward Biology, Catalysis, and Nanotechnology, Chem. Rev. 104 (2004) 293–346. doi:10.1021/cr030698+.

[2] A.S.K. Hashmi, G.J. Hutchings, Gold Catalysis, Angew. Chemie Int. Ed. 45 (2006) 7896–7936. doi:10.1002/anie.200602454.

ACCEPTED MANUSCRIPT

[3] K. Saha, S.S. Agasti, C. Kim, X. Li, V.M. Rotello, Gold Nanoparticles in Chemical and Biological Sensing, Chem. Rev. 112 (2012) 2739–2779. doi:10.1021/cr2001178.

[4] H. Zimmermann, a Lindgren, W. Schuhmann, L. Gorton, Anisotropic orientation of horseradish peroxidase by reconstitution on a thiol-modified gold electrode., Chemistry. 6 (2000) 592–9. doi:10.1002/(SICI)1521-3765(20000218)6:4<592::AID-CHEM592>3.0.CO;2-6.

[5] S. Shleev, A. Christenson, V. Serezhenkov, D. Burbaev, A. Yaropolov, L. Gorton, T. Ruzgas, Electrochemical redox transformations of T1 and T2 copper sites in native Trametes hirsuta laccase at gold electrode, Biochem. J. 385 (2005) 745–754. doi:10.1042/BJ20041015.

[6] S. Guo, E. Wang, Synthesis and electrochemical applications of gold nanoparticles, Anal. Chim. Acta. 598 (2007) 181–192. doi:10.1016/j.aca.2007.07.054.

[7] U. Wollenberger, R. Spricigo, S. Leimkühler, K. Schröder, Protein electrodes with direct electrochemical communication, Adv. Biochem. Eng. Biotechnol. 109 (2007) 19–64. doi:10.1007/10_2007_083.

[8] M. Brust, D. Bethell, C.J. Kiely, D.J. Schiffrin, Self-Assembled Gold Nanoparticle Thin Films with Nonmetallic Optical and Electronic Properties, Langmuir. 14 (1998) 5425–5429. doi:10.1021/la980557g.

[9] L. Sun, Y.A. Diaz-Fernandez, T.A. Gschneidtner, F. Westerlund, S. Lara-Avila, K. Moth-Poulsen, Single-molecule electronics: from chemical design to functional devices, Chem. Soc. Rev. 43 (2014) 7378–7411. doi:10.1039/C4CS00143E.

[10] V. Coman, R. Ludwig, W. Harreither, D. Haltrich, L. Gorton, T. Ruzgas, S. Shleev, A Direct Electron Transfer-Based Glucose/Oxygen Biofuel Cell Operating in Human Serum, Fuel Cells. 10 (2010) 9–16. doi:10.1002/fuce.200900121.

[11] S. Xu, S.D. Minteer, Enzymatic biofuel cell for oxidation of glucose to CO_2, ACS Catal. 2 (2012) 91–94. doi:10.1021/cs200523s.

[12] E. Katz, I. Willner, Integrated nanoparticle-biomolecule hybrid systems: Synthesis, properties, and applications, Angew. Chemie - Int. Ed. 43 (2004) 6042–6108. doi:10.1002/anie.200400651.

[13] D.A. Giljohann, D.S. Seferos, W.L. Daniel, M.D. Massich, P.C. Patel, C.A. Mirkin, Gold nanoparticles for biology and medicine, Angew. Chemie - Int. Ed. 49 (2010) 3280–3294. doi:10.1002/anie.200904359.

[14] D. Pissuwan, S.M. Valenzuela, M.B. Cortie, Therapeutic possibilities of plasmonically heated gold nanoparticles, Trends Biotechnol. 24 (2006) 62–67. doi:http://dx.doi.org/10.1016/j.tibtech.2005.12.004.

[15] J. Turkevich, P.C. Stevenson, J. Hillier, A study of the nucleation and growth processes in the synthesis of colloidal gold, Discuss. Faraday Soc. 11 (1951) 55–75. doi:10.1039/DF9511100055.

ACCEPTED MANUSCRIPT

[16] M. Brust, M. Walker, D. Bethell, D.J. Schiffrin, R. Whyman, Synthesis of thiol-derivatised gold nanoparticles in a two-phase Liquid-Liquid system, J. Chem. Soc. Chem. Commun. (1994) 801–802. doi:10.1039/C39940000801.

[17] M. Brust, J. Fink, D. Bethell, D.J. Schiffrin, C. Kiely, Synthesis and reactions of functionalised gold nanoparticles, J. Chem. Soc. Chem. Commun. (1995) 1655–1656. doi:10.1039/C39950001655.

[18] J. Zhang, A.C. Welinder, Q. Chi, J. Ulstrup, Electrochemically controlled self-assembled monolayers characterized with molecular and sub-molecular resolution., Phys. Chem. Chem. Phys. 13 (2011) 5526–5545. doi:10.1039/c0cp02183k.

[19] R.G. Nuzzo, D.L. Allara, Adsorption of bifunctional organic disulfides on gold surfaces, J. Am. Chem. Soc. 105 (1983) 4481–4483. doi:10.1021/ja00351a063.

[20] C.D. Bain, G.M. Whitesides, Molecular-Level Control over Surface Order in Self-Assembled Monolayer Films of Thiols on Gold, Science (80-.). 240 (1988) 62 LP-63. http://science.sciencemag.org/content/240/4848/62.abstract.

[21] G.E. Poirier, Characterization of Organosulfur Molecular Monolayers on Au(111) using Scanning Tunneling Microscopy, Chem. Rev. 97 (1997) 1117–1128. doi:10.1021/cr960074m.

[22] A.C. Templeton, M.J. Hostetler, E.K. Warmoth, S. Chen, C.M. Hartshorn, V.M. Krishnamurthy, M.D.E. Forbes, R.W. Murray, Gateway Reactions to Diverse, Polyfunctional Monolayer-Protected Gold Clusters, J. Am. Chem. Soc. 120 (1998) 4845–4849. doi:10.1021/ja980177h.

[23] R.G. Pearson, Hard and Soft Acids and Bases, J. Am. Chem. Soc. 85 (1963) 3533–3539. doi:10.1021/ja00905a001.

• [24] H. Häkkinen, The gold-sulfur interface at the nanoscale, Nat. Chem. 4 (2012) 443–455. http://dx.doi.org/10.1038/nchem.1352.

Important as a recent comprehensive overview of computational approaches to the gold-sulfur interface in ultra-high vacuum.

•• [25] J. Yan, R. Ouyang, P.S. Jensen, E. Ascic, D.A. Tanner, B. Mao, J. Zhang, C. Tang, N.S. Hush, J. Ulstrup, J.R. Reimers, Controlling the stereochemistry and regularity of butanethiol self-assembled monolayers on Au(111), J. Am. Chem. Soc. 136 (2014) 17087–17094. doi:10.1021/ja508100c.

This paper is unique in demonstrating structural diversity and two alkanethiol binding modes on the same Au(111)-electrode surface.

[26] N.J. Kay, S.J. Higgins, J.O. Jeppesen, E. Leary, J. Lycoops, J. Ulstrup, R.J. Nichols, Single-Molecule Electrochemical Gating in Ionic Liquids, J. Am. Chem. Soc. 134 (2012) 16817–16826. doi:10.1021/ja307407e.

ACCEPTED MANUSCRIPT

[27] I. V Pobelov, Z. Li, T. Wandlowski, Electrolyte Gating in Redox-Active Tunneling Junctions—An Electrochemical STM Approach, J. Am. Chem. Soc. 130 (2008) 16045–16054. doi:10.1021/ja8054194.

•• [28] S. Martín, I. Grace, M.R. Bryce, C. Wang, R. Jitchati, A.S. Batsanov, S.J. Higgins, C.J. Lambert, R.J. Nichols, Identifying Diversity in Nanoscale Electrical Break Junctions, J. Am. Chem. Soc. 132 (2010) 9157–9164. doi:10.1021/ja103327f.

Unique as a study demonstrating the combination of Au-S bonding and other atomic Au-contacts, with π-stacking in molecular scale junctions.

[29] P. Salvatore, A. Glargaard Hansen, K. Moth-Poulsen, T. Bjornholm, R. John Nichols, J. Ulstrup, Voltammetry and in situ Scanning tunnelling spectroscopy of osmium, iron, and ruthenium complexes of 2,2′:6′,2″-terpyridine covalently linked to Au(111)-electrodes, Phys. Chem. Chem. Phys. 13 (2011) 14394–14403. doi:10.1039/C1CP21197H.

[30] J. Zhang, Q. Chi, J.U. Nielsen, E.P. Friis, J.E.T. Andersen, J. Ulstrup, Two-dimensional cysteine and cystine cluster networks on Au (111) disclosed by voltammetry and in situ scanning tunneling microscopy, Langmuir. 16 (2000) 7229–7237. doi:10.1021/la000246h.

[31] J. Zhang, Q. Chi, J. Ulstrup, Assembly dynamics and detailed structure of 1-propanethiol monolayers on Au (111) surfaces observed real time by in situ STM, Langmuir. 22 (2006) 6203–6213. doi:10.1021/la0605891.

[32] Y. Wang, Q. Chi, N.S. Hush, J.R. Reimers, J. Zhang, J. Ulstrup, Scanning tunneling microscopic observation of adatom-mediated motifs on gold- thiol self-assembled monolayers at high coverage, J. Phys. Chem. C. 113 (2009) 19601–19608. doi:10.1021/jp906216k.

[33] Y. Wang, Q. Chi, N.S. Hush, J.R. Reimers, J. Zhang, J. Ulstrup, Gold mining by alkanethiol radicals: Vacancies and pits in the self-assembled monolayers of 1-propanethiol and 1-butanethiol on Au(111), J. Phys. Chem. C. 115 (2011) 10630–10639. doi:10.1021/jp111811g.

• [34] J.M. Artés, M. López-Martínez, I. Díez-Pérez, F. Sanz, P. Gorostiza, Conductance Switching in Single Wired Redox Proteins, Small. 10 (2014) 2537–2541. doi:10.1002/smll.201303753.

Important as a case for multiple Cys mutation and covalent Au-S surface binding with prospects for conductivity pathway mapping through a redox metalloprotein.

[35] Y. Wang, Q. Chi, J. Zhang, N.S. Hush, J.R. Reimers, J. Ulstrup, Chain-branching control of the atomic structure of alkanethiol-based gold--sulfur interfaces, J. Am. Chem. Soc. 133 (2011) 14856–14859. doi:10.1021/ja204958h.

[36] J. Zhang, A. Bilič, J.R. Reimers, N.S. Hush, J. Ulstrup, Coexistence of multiple conformations in cysteamine monolayers on Au(111), J. Phys. Chem. Part B Condens. Matter, Mater. Surfaces, Interfaces Biophys. 109 (2005) 15355–15367.

ACCEPTED MANUSCRIPT

[37] R. Ouyang, J. Yan, P.S. Jensen, E. Ascic, S. Gan, D.A. Tanner, B. Mao, L. Niu, J. Zhang, C. Tang, N.S. Hush, J.R. Reimers, J. Ulstrup, Intermixed Adatom and Surface-Bound Adsorbates in Regular Self-Assembled Monolayers of Racemic 2-Butanethiol on Au(111), ChemPhysChem. 16 (2015) 928–932. doi:10.1002/cphc.201402904.

[38] A. Bilič, J.R. Reimers, N.S. Hush, The structure, energetics, and nature of the chemical bonding of phenylthiol adsorbed on the Au(111) surface: Implications for density-functional calculations of molecular-electronic conduction, J. Chem. Phys. 122 (2005). doi:http://dx.doi.org/10.1063/1.1850455.

[39] Y. Wang, N.S. Hush, J.R. Reimers, Understanding the Chemisorption of 2-Methyl-2-propanethiol on Au(111), J. Phys. Chem. C. 111 (2007) 10878–10885. doi:10.1021/jp068833k.

•• [40] J.R. Reimers, M.J. Ford, A. Halder, J. Ulstrup, N.S. Hush, Gold surfaces and nanoparticles are protected by Au(0)–thiyl species and are destroyed when Au(I)–thiolates form, Proc. Natl. Acad. Sci. . 113 (2016) E1424–E1433. doi:10.1073/pnas.1600472113.

Paper unique in describing in great detail the Au-S bonding and electronic structure.

•• [41] P. Maksymovych, D.C. Sorescu, J.T. Yates, Gold-Adatom-Mediated Bonding in Self-Assembled Short-Chain Alkanethiolate Species on the Au(111) Surface, Phys. Rev. Lett. 97 (2006) 146103. doi:10.1103/PhysRevLett.97.146103.

Paper unique by introducing the gold-adatom notion in alkanethiol binding to well-defined gold surfaces.

[42] R. Mazzarello, A. Cossaro, A. Verdini, R. Rousseau, L. Casalis, M.F. Danisman, L. Floreano, S. Scandolo, A. Morgante, G. Scoles, Structure of a CH_3S Monolayer on Au(111) Solved by the Interplay between Molecular Dynamics Calculations and Diffraction Measurements, Phys. Rev. Lett. 98 (2007) 16102. doi:10.1103/PhysRevLett.98.016102.

[43] A. Cossaro, R. Mazzarello, R. Rousseau, L. Casalis, A. Verdini, A. Kohlmeyer, L. Floreano, S. Scandolo, A. Morgante, M.L. Klein, G. Scoles, X-ray Diffraction and Computation Yield the Structure of Alkanethiols on Gold(111), Science (80-.). 321 (2008) 943–946. doi:10.1126/science.1158532.

[44] A. Chaudhuri, M. Odelius, R.G. Jones, T.-L. Lee, B. Detlefs, D.P. Woodruff, The structure of the Au(111)/methylthiolate interface: New insights from near-edge x-ray absorption spectroscopy and x-ray standing waves, J. Chem. Phys. 130 (2009). doi:http://dx.doi.org/10.1063/1.3102095.

[45] P.D. Jadzinsky, G. Calero, C.J. Ackerson, D.A. Bushnell, R.D. Kornberg, Structure of a Thiol Monolayer-Protected Gold Nanoparticle at 1.1 Å Resolution, Science (80-.). 318 (2007) 430–433. doi:10.1126/science.1148624.

[46] Q. Chi, J. Zhang, J. Ulstrup, Surface microscopic structure and electrochemical rectification of a branched alkanethiol self-assembled monolayer, J. Phys. Chem. B. 110 (2006) 1102–1106. doi:10.1021/jp056356k.

ACCEPTED MANUSCRIPT

[47] P.F. Cafe, A.G. Larsen, W.R. Yang, A. Bilič, I.M. Blake, M.J. Crossley, J. Zhang, H. Wackerbarth, J. Ulstrup, J.R. Reimers, Chemisorbed and physisorbed structures for 1,10-phenanthroline and dipyrido[3,2-a : 2 ',3 '-c]phenazine on Au(111), J. Phys. Chem. Part C Nanomater. Interfaces Hard Matter. 111 (2007) 17285–17296. doi:10.1021/jp0736591.

•• [48] J. Zhang, A.M. Kuznetsov, I.G. Medvedev, Q. Chi, T. Albrecht, P.S. Jensen, J. Ulstrup, Single-molecule electron transfer in electrochemical environments, Chem. Rev. 108 (2008) 2737–2791. doi:10.1021/cr068073%2B.

Describes comprehensively single-molecule structure and dynamics of redox metalloproteins and DNA-based molecules bound to Au(111)-electrode surfaces via Au-S bonding.

[49] N. Zhu, X. Hao, J. Ulstrup, Q. Chi, Single-Nanoparticle Resolved Biomimetic Long-Range Electron Transfer and Electrocatalysis of Mixed-Valence Nanoparticles, ACS Catal. 6 (2016) 2728–2738. doi:10.1021/acscatal.6b00411.

• [50] E.A. Della Pia, Q. Chi, J.E. Macdonald, J. Ulstrup, D.D. Jones, M. Elliott, Fast electron transfer through a single molecule natively structured redox protein., Nanoscale. 4 (2012) 7106–13. doi:10.1039/c2nr32131a.

Important as a case for a redox metalloprotein hooked on to enclosing Au(111)-electrode and soft metal tip via binding of mutant Cys residues, leading to very high single-molecule conductivity.

[51] A. Alessandrini, M. Gerunda, G.W. Canters, M.P. Verbeet, P. Facci, Electron tunnelling through azurin is mediated by the active site Cu ion, Chem. Phys. Lett. 376 (2003) 625–630. doi:http://dx.doi.org/10.1016/S0009-2614(03)01020-0.

[52] A.G. Hansen, P. Salvatore, K.K. Karlsen, R.J. Nichols, J. Wengel, J. Ulstrup, Electrochemistry and in situ scanning tunnelling microscopy of pure and redox-marked DNA- and UNA-based oligonucleotides on Au(111)-electrode surfaces., Phys. Chem. Chem. Phys. 15 (2013) 776–86. doi:10.1039/c2cp42351k.

[53] P. Salvatore, D. Zeng, K.K. Karlsen, Q. Chi, J. Wengel, J. Ulstrup, Electrochemistry of single metalloprotein and DNA-based molecules at Au(111) electrode surfaces, ChemPhysChem. 14 (2013) 2101–2111. doi:10.1002/cphc.201300299.

[54] Q. Chi, J. Zhang, J.U. Nielsen, E.P. Friis, I. Chorkendorff, G.W. Canters, J.E.T. Andersen, J. Ulstrup, Molecular Monolayers and Interfacial Electron Transfer of Pseudomonas aeruginosa Azurin on Au(111), J. Am. Chem. Soc. 122 (2000) 4047–4055. doi:10.1021/ja993174t.

[55] A.L. Furst, M.G. Hill, J.K. Barton, A Multiplexed, Two-Electrode Platform for Biosensing Based on DNA-Mediated Charge Transport, Langmuir. 31 (2015) 6554–6562. doi:10.1021/acs.langmuir.5b00829.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

[56] T.G. Drummond, M.G. Hill, J.K. Barton, Electrochemical DNA sensors, Nat Biotech. 21 (2003) 1192–1199. http://dx.doi.org/10.1038/nbt873.

[57] K.J. Odenthal, J.J. Gooding, An introduction to electrochemical DNA biosensors, Analyst. 132 (2007) 603–610. doi:10.1039/B701816A.

[58] E.E. Ferapontova, V.G. Grigorenko, A.M. Egorov, T. Börchers, T. Ruzgas, L. Gorton, Mediatorless biosensor for H_2O_2 based on recombinant forms of horseradish peroxidase directly adsorbed on polycrystalline gold, Biosens. Bioelectron. 16 (2001) 147–157. doi:http://dx.doi.org/10.1016/S0956-5663(01)00134-8.

[59] L.D. Burke, P.F. Nugent, The electrochemistry of gold: II the electrocatalytic behaviour of the metal in aqueous media, Gold Bull. 31 (1998) 39–50. doi:10.1007/BF03214760.

[60] C. Amatore, S. Arbault, M. Guille, F. Lemaître, Electrochemical Monitoring of Single Cell Secretion: Vesicular Exocytosis and Oxidative Stress, Chem. Rev. 108 (2008) 2585–2621. doi:10.1021/cr068062g.

[61] F.A. Armstrong, Insights from protein film voltammetry into mechanisms of complex biological electron-transfer reactions, J. Chem. Soc. Dalt. Trans. (2002) 661–671. doi:10.1039/B108359G.

[62] F.A. Armstrong, N.L. Barlow, P.L. Burn, K.R. Hoke, L.J.C. Jeuken, C. Shenton, G.R. Webster, Fast, long-range electron-transfer reactions of a “blue” copper protein coupled non-covalently to an electrode through a stilbenyl thiolate monolayer, Chem. Commun. (2004) 316–317. doi:10.1039/B312936E.

[63] A.C. Welinder, J. Zhang, A.G. Hansen, K. Moth-Poulsen, H.E.M. Christensen, A. Kuznetsov, T. Bjørnholm, J. Ulstrup, Voltammetry and Electrocatalysis of *Achromobacter Xylosoxidans* Copper Nitrite Reductase on Functionalized Au (111)-Electrode Surfaces, Zeitschrift Für Phys. Chemie. 221 (2007) 1343–1378. doi:10.1524/zpch.2007.221.9-10.1343.

[64] X. Hao, J. Zhang, H.E.M. Christensen, H. Wang, J. Ulstrup, Electrochemical Single-Molecule AFM of the Redox Metalloenzyme Copper Nitrite Reductase in Action, ChemPhysChem. 13 (2012) 2919–2924. doi:10.1002/cphc.201200220.

[65] A.C. Welinder, J. Zhang, D.B. Steensgaard, J. Ulstrup, Adsorption of human insulin on single-crystal gold surfaces investigated by in situ scanning tunnelling microscopy and electrochemistry, Phys. Chem. Chem. Phys. 12 (2010) 9999–10011. doi:10.1039/c0cp01021a.

[66] Q. Chi, O. Farver, J. Ulstrup, Long-range protein electron transfer observed at the single-molecule level: In situ mapping of redox-gated tunneling resonance., Proc. Natl. Acad. Sci. U. S. A. 102 (2005) 16203–16208. doi:10.1073/pnas.0508257102.

[67] B. Bonanni, D. Alliata, A.R. Bizzarri, S. Cannistraro, Topological and Electron-Transfer Properties of Yeast Cytochrome *c* Adsorbed on Bare Gold Electrodes, ChemPhysChem. 4 (2003) 1183–1188. doi:10.1002/cphc.200300784.

ACCEPTED MANUSCRIPT

[68] A.G. Hansen, A. Boisen, J.U. Nielsen, H. Wackerbarth, I. Chorkendorff, J.E.T. Andersen, J. Zhang, J. Ulstrup, Adsorption and interfacial electron transfer of *Saccharomyces cerevisiae* yeast cytochrome *c* monolayers on Au(111) electrodes, Langmuir. 19 (2003) 3419–3427.

• [69] J.R. Reimers, Y. Wang, B.O. Cankurtaran, M.J. Ford, Chemical Analysis of the Superatom Model for Sulfur-Stabilized Gold Nanoparticles, J. Am. Chem. Soc. 132 (2010) 8378–8384. doi:10.1021/ja101083v.

Important to understand the detailed electronic structure of molecular scale nanoparticles.

[70] P. Maksymovych, O. Voznyy, D.B. Dougherty, D.C. Sorescu, J.T. Yates Jr., Gold adatom as a key structural component in self-assembled monolayers of organosulfur molecules on Au(111), Progr. Surf. Sci. 85 (2010) 206–240. doi:http://dx.doi.org/10.1016/j.progsurf.2010.05.001.

[71] C.A. Alves, E.L. Smith, M.D. Porter, Atomic scale imaging of alkanethiolate monolayers at gold surfaces with atomic force microscopy, J. Am. Chem. Soc. 114 (1992) 1222–1227. doi:10.1021/ja00030a015.

[72] P. Pyykkö, Theoretical Chemistry of Gold, Angew. Chemie Int. Ed. 43 (2004) 4412–4456. doi:10.1002/anie.200300624.

[73] G.J. Hutchings, M. Brust, H. Schmidbaur, Gold-an introductory perspective, Chem. Soc. Rev. 37 (2008) 1759–1765. doi:10.1039/B810747P.

[74] R.K. Chadha, R. Kumar, D.G. Tuck, The direct electrochemical synthesis of thiolato complexes of copper, silver, and gold; the molecular structure of $[Cu(SC_6H_4CH_3\text{-}o)$ (1,10-phenanthroline)$]_2 \bullet CH_3CN$, Can. J. Chem. 65 (1987) 1336–1342. doi:10.1139/v87-224.

* [75] P.K. Das, S. Samanta, A.B. McQuarters, N. Lehnert, A. Dey, Valence tautomerism in synthetic models of cytochrome P450, Proc. Natl. Acad. Sci. 113 (2016) 6611–6616. doi:10.1073/pnas.1600525113.

Important as it shows a simpler form of the same type of effects in which dispersion competes with covalent and ionic bonding motifs.

[76] J.C. Love, L.A. Estroff, J.K. Kriebel, R.G. Nuzzo, G.M. Whitesides, Self-Assembled Monolayers of Thiolates on Metals as a Form of Nanotechnology, Chem. Rev. 105 (2005) 1103–1170. doi:10.1021/cr0300789.

[77] M.H. McAdon, W.A. Goddard, Charge density waves, spin density waves, and Peierls distortions in one-dimensional metals. 2. Generalized valence bond studies of copper, silver, gold, lithium and sodium, J. Phys. Chem. 92 (1988) 1352–1365. doi:10.1021/j100316a067.

[78] M.H. McAdon, W.A. Goddard, Charge density waves, spin density waves, and Peierls distortions in one-dimensional metals. I. Hartree–Fock studies of Cu, Ag, Au, Li, and Na, J. Chem. Phys. 88 (1988).

ACCEPTED MANUSCRIPT

[79] H. Schmidbaur, A. Schier, A briefing on aurophilicity, Chem. Soc. Rev. 37 (2008) 1931–1951. doi:10.1039/B708845K.

[80] J.J. Gooding, S. Ciampi, The molecular level modification of surfaces: from self-assembled monolayers to complex molecular assemblies, Chem. Soc. Rev. 40 (2011) 2704–2718. doi:10.1039/C0CS00139B.

[81] J. Zhang, J. Ulstrup, Oxygen-free in situ scanning tunnelling microscopy, J. Electroanal. Chem. 599 (2007) 213–220. doi:10.1016/j.jelechem.2006.02.011.

ACCEPTED MANUSCRIPT

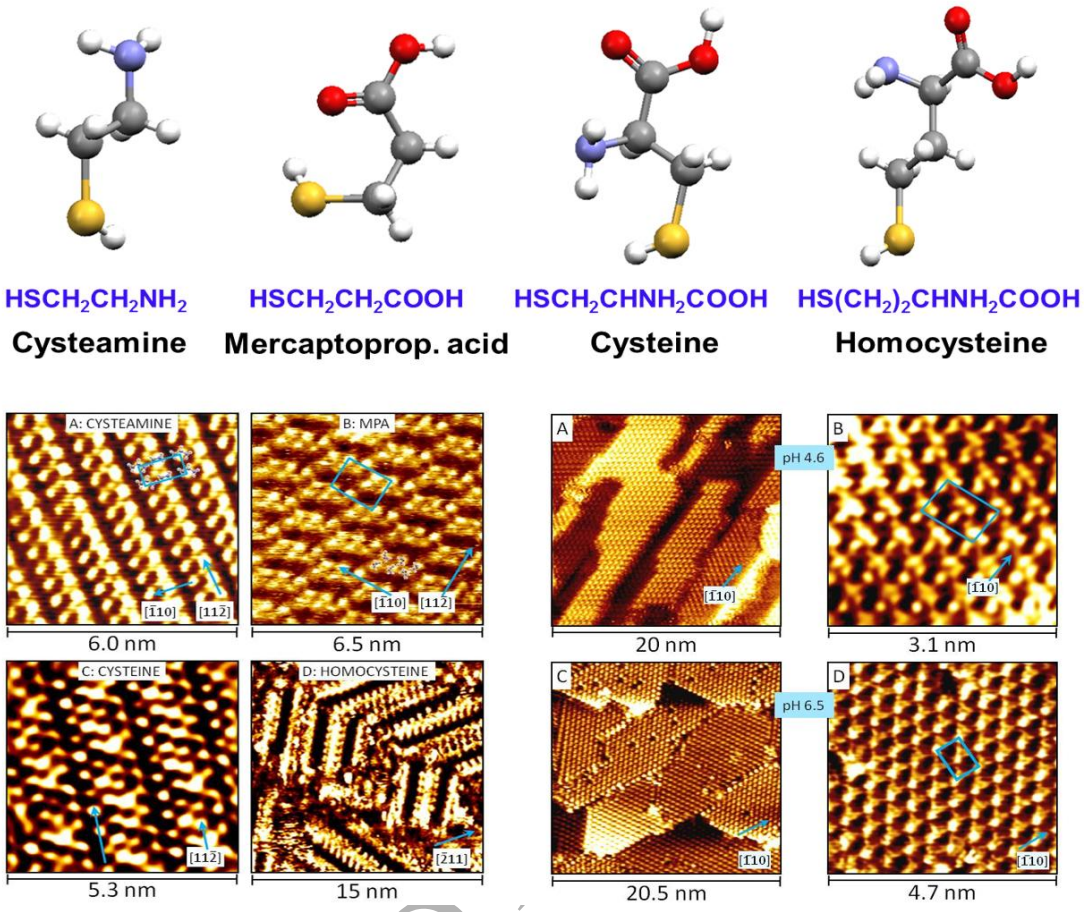

Fig.1. Examples of functionalized alkanethiols studied by single-crystal voltammetry and in situ STM. Top row: Molecular structures. Bottom rows: High-resolution in situ STM images. The four images to the left are the molecules indicated, on Au(111). The four images to the right show cysteine on Au(110), with sub-molecular resolution images. Adapted from ref 48.

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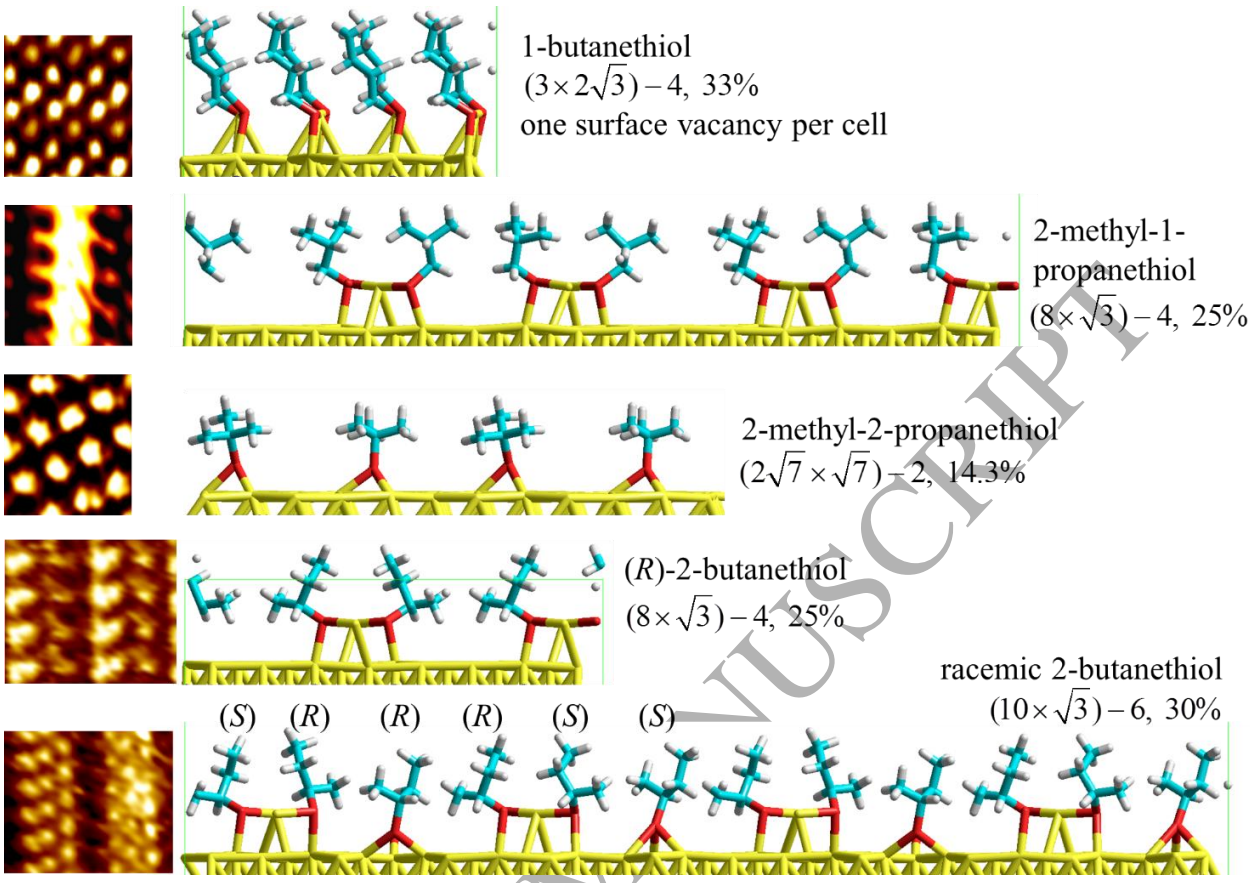

Fig. 2. Shown on the left are observed STM images of the butanethiol family on Au(111), with their surface-cell parameters, coverages, and interpreted atomic structures shown on the right. Two copies of each unit cell are shown in each structure.

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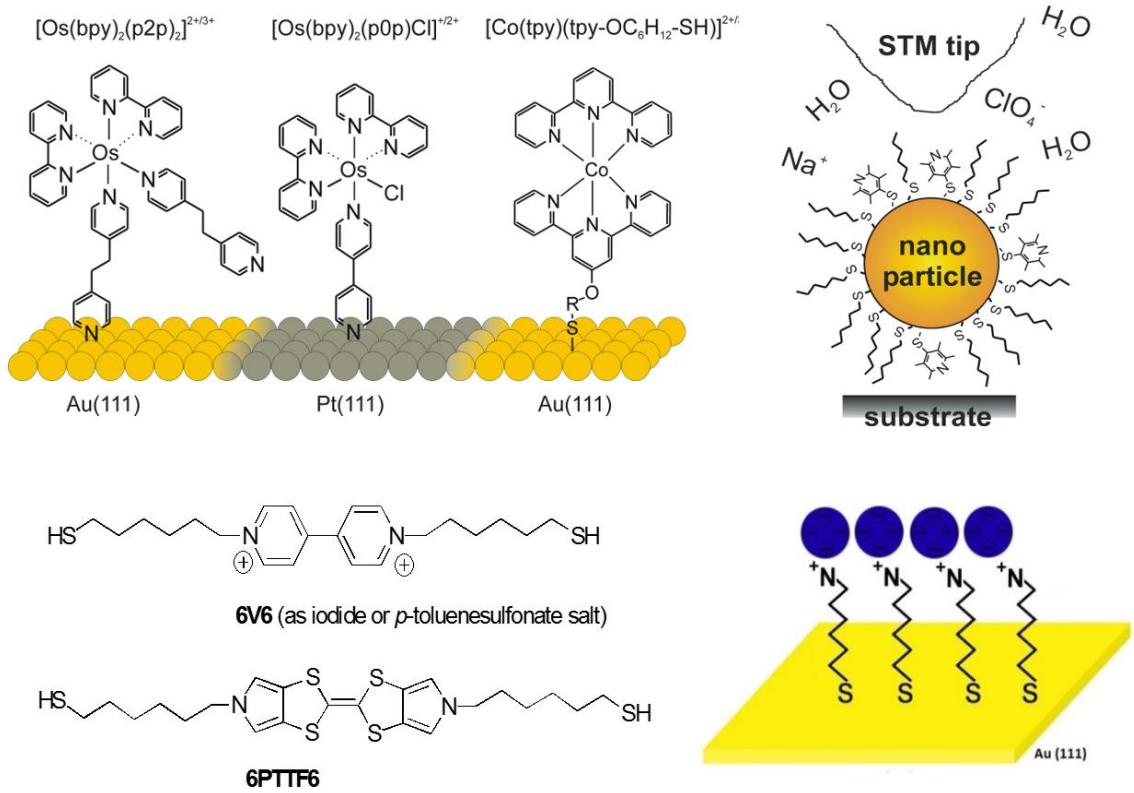

Fig.3. Redox molecules surface linked by Au-S or related bonding studied by single-crystal voltammetry and in situ STM. Top left: transition metal complexes [Ref 48]. Top right: Au-S coated Au-nanoparticles [Ref 48]. Bottom left: viologen and *p*-tetrathiafulvalene with S-linker groups [Ref 26]. Bottom right: Molecular scale Prussian Blue nanoparticles linked to Au(111)-surfaces via ω-NH_3^+-functionalized alkanethiols [Ref 49].

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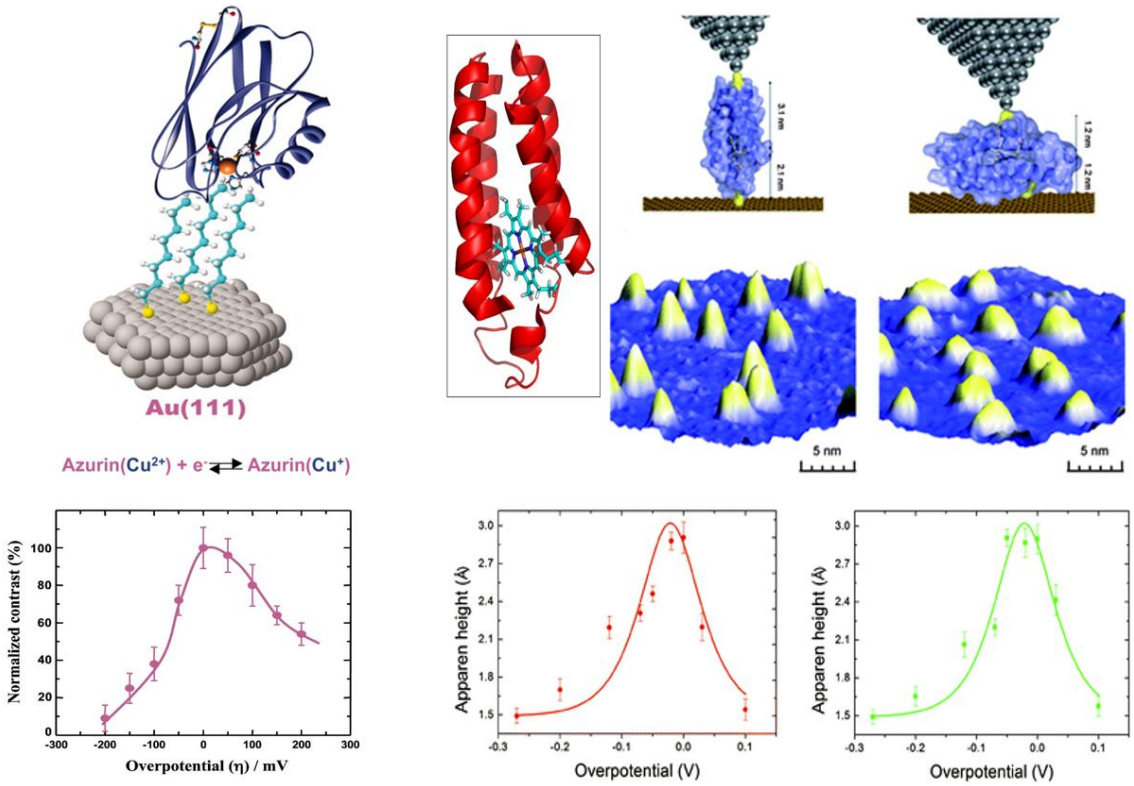

Fig.4. Metalloproteins linked to Au-surfaces either via alkanethiol SAMs or directly via surface cysteine residues, studied by single-crystal voltammetry and in-situ STM.

Top row: Schematic view of azurin (left) and cyt b_{562} (right) on the Au(111)-surfaces.

Bottom row: In situ STS of the proteins indicated. Adapted from ref 50 and 66.

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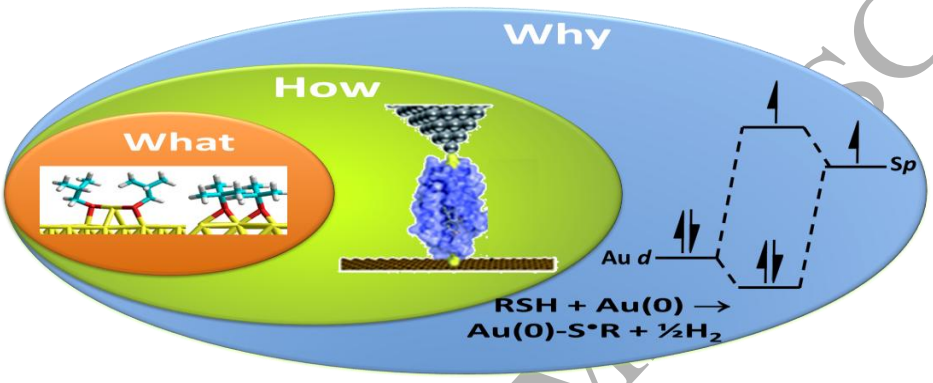
Graphical abstract (5x13):

Gold surfaces and gold nanoparticles are widely used. The surfaces and nanoparticles often have to be coated by sulfur-bound organic ligands, which both provide stability and participate in many desired processes. We overview here what, how, and why it is that the core Au-S surface bond offers such versatile structure and function.



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